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Transient liquid phase bonding of AA-6063 to UNS S32304 using Cu interlayer

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Abstract

Transient liquid phase bonding of AA-6063 and UNS S32304 was performed in an inert atmosphere using a Gleeble (model 3800) thermo-mechanical simulator. Base metals were machined to rectangular dimensions of 30mm x 15mm. Aluminum samples were fabricated from a U-shaped extruded Al-6063 profile with 2mm thick, while duplex stainless steel samples were in form of coupons with 1mm thick. A copper foil with 99.9% purity and 10µm thickness was used as an interlayer between the base metal sheets. A compression load of 0.2KN was applied horizontally to the specimens. The effect of bonding temperature (550°C, 555°C, 560°C and 570°C) was studied on the microstructure of the joints using light and scanning electron microscopy. Compositional changes across the joint region were studied using energy dispersive X-ray spectroscopy. Although copper diffusion into aluminum results in an Al-Cu eutectic structure, the oxide layer on the aluminum surface controls the dissolution behavior of Cu and extent of wettability with the base metals. Although a defect free joint was produced at 570°C, X-ray diffraction results detected the formation of intermetallic compounds ($FeAl_3$).

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Keywords: TLP bonding; Aluminum alloys; Duplex stainless steel.

1. Introduction

There is a growing demand for cost effective materials with enhanced engineered properties and this involves the use of dissimilar metals. Although dissimilar metals are being used in the aerospace and oil and gas sectors, the joining of dissimilar metals is still facing numerous challenges and difficulties when compared to the joining of metals with similar compositions. The wide difference in melting points and thermal expansion coefficients of

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dissimilar metals can result in residual stresses within the joint region and this can result in a failure of the joint when conventional fusion welding is used. The formation of intermetallic compounds (IMCs) can easily result in brittle failure of the welding joints.[1-3]

Several methods can be used to join dissimilar metals. Each one has its own advantages and limitations. Selecting the most appropriate method is vital for accomplishing successful joints. Fusion welding processes, solid-state joining, adhesive bonding and brazing and soldering are the most well-known methods for joining dissimilar metals. Unlike fusion welding, solid state diffusion bonding does not require melting of base metals. It can also be considered as a versatile process in terms of work piece thickness and geometry, however the numbers of published articles on diffusion bonding and hybrid joining processes are still quite few compared to arc welding process like: gas tungsten arc welding (GTAW), shielded metal arc welding (SMAW) and gas metal arc welding (GMAW).

Transient liquid phase (TLP) bonding is a type of liquid diffusion welding process, which involves the use of an interlayer placed between the two parent surfaces, heating will be applied to the clamped components to reach a temperature; which is higher than the eutectic liquid temperature of the base metals (aluminum and stainless steel) and filler (copper) until the joint region solidifies isothermally.[4,5] In addition to its lower processing temperature compared to fusion welding[6], TLP has other advantages such as: ability to weld parts with complex geometries and small thickness.[7]

The aim of this research to achieve a sound joint between 6063 aluminum alloy (AA-6063) and duplex stainless steel (UNS S32304) at a temperature lower than conventional welding processes with the advantage of minimizing intermetallic formation by isothermal solidification.

2. Experimental

UNS S32304 and AA-6063 were supplied by (ThyssenKrupp Nirosta, Germany) and (Qalex, Qatar) respectively. Both samples were machined to rectangular dimensions of 30mm X 15mm. Aluminum samples were fabricated from an extruded AA-6063 sheet of 2mm thickness, while duplex stainless steel samples were in the form of coupons witha thickness of 1mm. A copper foil with 99.9% purity and 10μm thickness was obtained from (Goodfellow, UK) was used as an interlayer between the Al and stainless steel sheets.The base metals were polished to 1000 grit surface finish using SiC paper, cleaned with ethanol and dried using hot air. Each joint consisted of 2 overlapped samples and a piece of copper foil sandwiched between them.

The TLP process was conducted using a thermo-mechanical physical simulator called the Gleeble system (model 3800) with a heating and cooling rate of 100°C/min. A thermocouple wire was welded to the edge of Al sample; approximately in the middle of the overlap region at 40 volts using a thermocouple welder (Dynamic system – model 35200).It was connected to the system to ensure an accurate feedback control of specimen temperatures. A compression load of 0.2KN was applied horizontally to the specimens. Bonding temperature was varied between 550°C, 555°C, 560°C and 570°C. Fig.1 shows a demonstration of one sample in the Gleeble system.

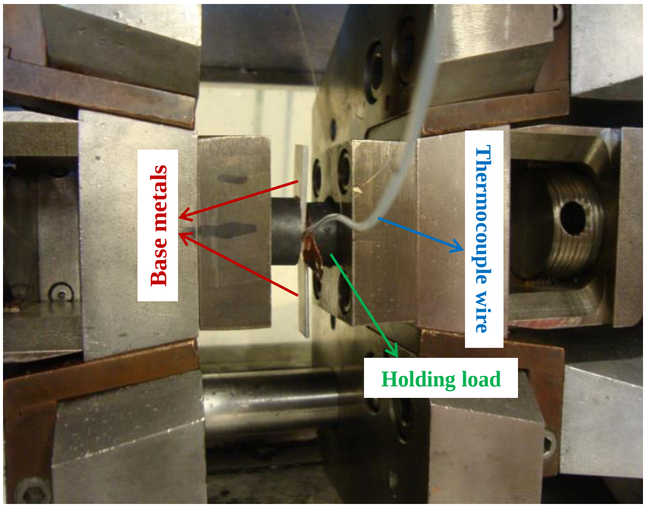

Fig.1. Illustration of a sample subjected to TLP bonding process in the Gleeble system.

The dissolution of Cu interlayer and joint interface of the processed samples were characterized by scanning electron microscope (SEM, Nova NanoSem 450) equipped with energy dispersive X-ray spectroscopy (EDX) and X-ray diffraction analysis (XRD, Rigaku ultima IV). An optical microscope (Leica DM IRM) equipped with Clemex image analysis software was used to measure the size of aluminum grains.

3. Results and discussion

3.1. Microstructure of joints and Cu diffusivity path

Fig.2 and table 1 show the EDX analysis for four points across the interface between the UNS S32304 and AA-6063. It can be noticed that Cu melted and diffused into the AA-6063, however EDX analysis did not detect any Cu traces in the UNS S32304 side. This could be attributed to the wide difference between the diffusion coefficients of Cu in Al ($D_{Cu \rightarrow Al}$) and Cu in Fe ($D_{Cu \rightarrow Fe}$), which are $\mathbf{2.1 \times 10^{-7} cm^2/s}$ [8] and $\mathbf{2.2 \times 10^{-13} cm^2/s}$ [9] at 920°C respectively. The $D_{Cu \rightarrow Al}$ is higher by a factor of $\mathbf{1 \times 10^6}$ than $D_{Cu \rightarrow Fe}$ .Liquid phase diffusion was the dominated diffusion mechanism and that most of the Cu atoms diffused into Al to make a eutectic reaction with it. However, after etching the UNS S32304 side with Kalling's reagent, less than 1wt% of Cu (≈0.90wt%) was detected (see fig 3 and table 2). M.Atabaki et al (2013) studied the diffusion bonding of stainless steel 304 using 50µm Cu foil as an interlayer. Although the welding temperatures were varied from 900°C to 1000°C, no voids were detected at the interface region and the copper side showed absence of any detectable diffusion zone.[10]

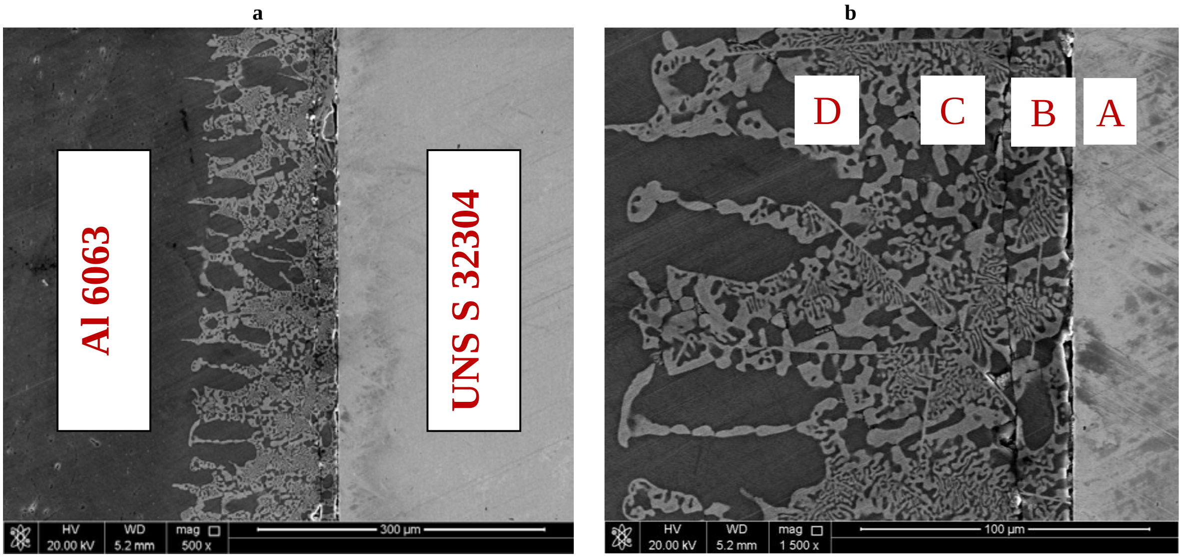

Fig.2. SEM images of sample bonded at 550C (a) microstructure at 500X; (b) enlarged microstructure showing different zones.

Table 1. EDX analysis of zones in fig.2-b.

Region	Fe [wt.%]	Al [wt.%]	Cu [wt.%]	Cr [wt.%]	Ni [wt.%]	Mg [wt.%]	Si [wt.%]	Mn[wt.%]
A	74.39	0.18	___	20.68	4.57	___	0.17	___
B	0.58	81.72	15.80	0.4	0.18	0.96	___	0.37
C	0.21	66.27	32.02	___	0.09	1.15	0.26	___
D	0.06	93.29	5.74	0.09	___	0.80	0.01	___

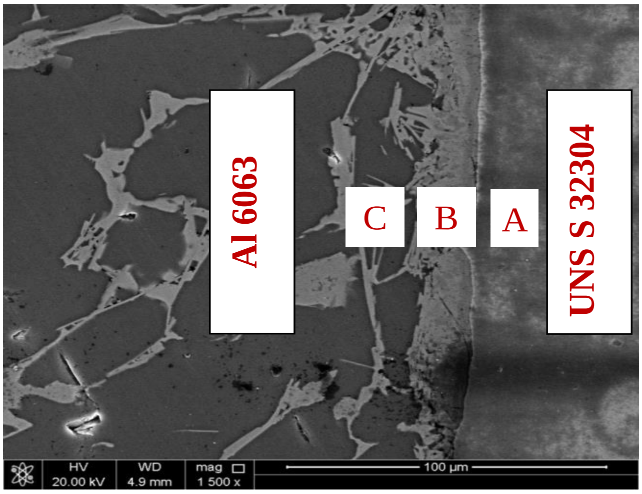

Fig.3. SEM image of sample joined at 570°C.

Table 2. EDX analysis of zones in fig.3.

Region	Fe [wt.%]	Al [wt.%]	Cu [wt.%]	Cr [wt.%]	Mg [wt.%]	Si [wt.%]
A	70.71	3.28	0.90	22.23	___	0.23
B	16.97	61.63	12.79	8.60	___	___
C	4.85	71.96	19.45	2.47	1.27	___

R.Qiu (2010) reported that interfacial reaction layer thickness (X) has a relationship with interaction time (t) and temperature (T) as per equation 1:[11]

$$x = (2Kt)^{0.5}$$
$$K = K_0 exp(-Q/RT) \quad (1)$$

Where, K is growth velocity (m2/s); K_0 is growth constant (m2/s); R is the gas constant (8.314KJ/mol) and Q is activation energy (KJ/mol). [11]

Fig.4 shows the effect of temperature on the thickness of Al-Cu eutectic structure, where the average width for diffusion bonded joints made at 550°C was measured to be100µm. In comparison joints made at 560°C gave a width of 194 µm.

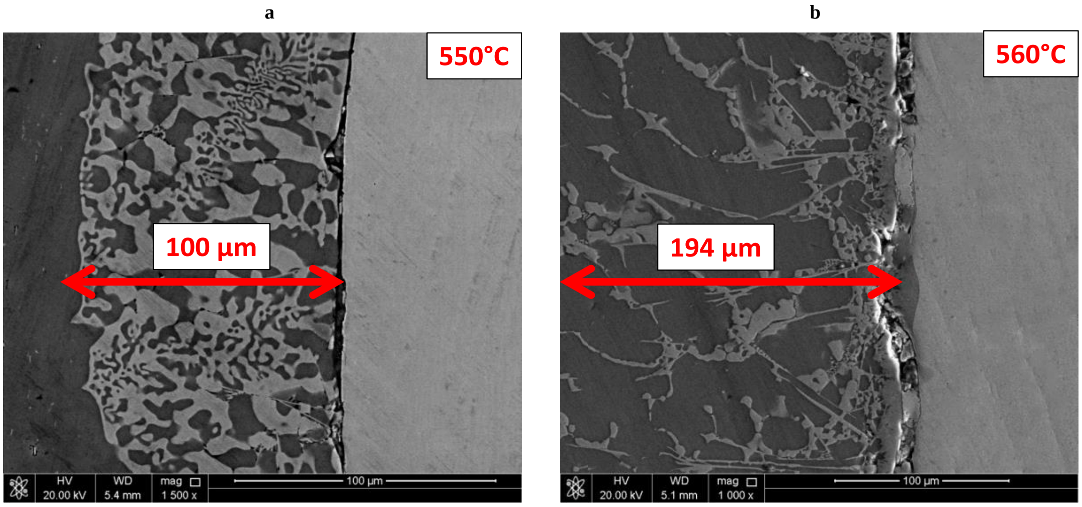

Fig.4. Effect of temperature on interaction layer thickness (a)550°C; (b)560°C.

XRD analysis detected the formation of $FeAl_3$, Which means that Al reacted with Fe and the interlayer does not prevent the formation of IMC (see fig.5).

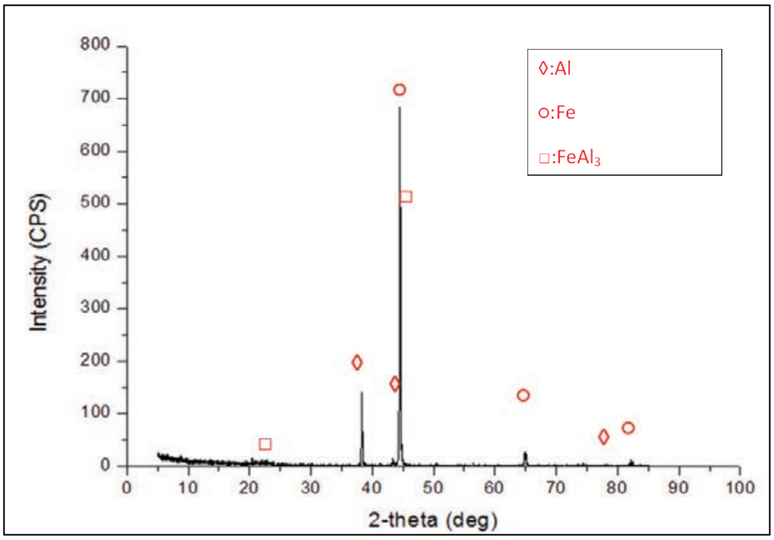

Fig.5. XRD result of joint produced at 570°C.

Fig.6 shows the microstructure of post welded AA-6063 etched with Weck's reagent.

a b

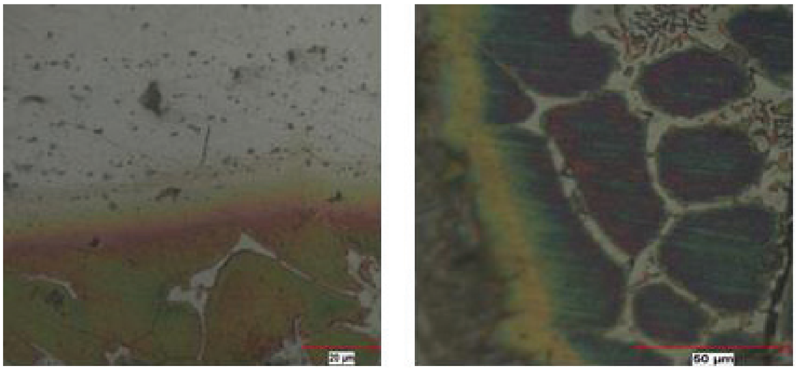

Fig.6. Microstrucutre of AA-6063 after joining process (a)100X; (b) 500X.

Microstructural observations in fig.6 show that Cu diffuses from the joint interface and into Al-6063 along grain boundaries. Therefore, grain boundary diffusion is dominant over lattice diffusion during the bonding process. The diffusivity paths depend on several features such as microstructure, temperature and the interface quality between the metal and adjacent layers.[12] Arrhenius law describes the effect of activation energy (E_a) on the diffusion coefficient (D) (see equation 2).

$$D = D_0 e^{-E_a/RT} \tag{2}$$

The ratio of E_a to the average kinetic energy (RT) has an inverse relationship with D (considering the negative sign), which means that diffusion rate increases with high temperature and low activation energy and vice versa. Since the ratio occur in an exponent, its effect on the overall rate is quite significant.

Fig.7 shows the microstructure of UNS S32304 after etching with Kalling's reagent. Unlike aluminum, diffusion of Cu atoms into UNS S32304 made the etchant used for as-received sample aggressive on the post welded ones. In just a few secondsthe sample became over etched and microstructure could not be observed. It wasalso noticed that ferrite grains (α-Fe) were so influenced by the etching solution compared to austenite grains (γ-Fe).This could be attributed to the significant difference between Cu diffusivities in α-Fe and γ-Fe ($4.4x10^{-9}$ and $9.4x10^{-12}$ cm^2/s , respectively). In addition, α-Fe has a more open atomic structure than γ-Fe.[13, 14]

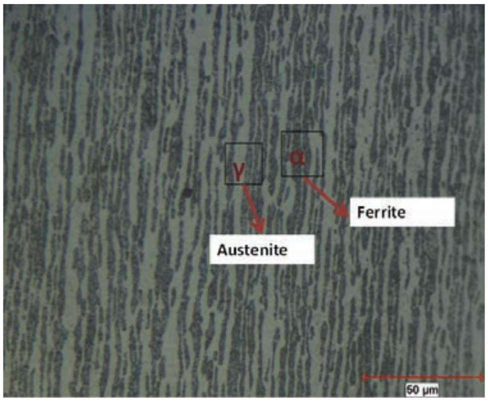

Fig.7. Microstructure of duplex stainless steel after joining process.

3.2. Grain size analysis

The rapid cooling rate affected the grain size of aluminum and made it finer; cooling rate has an inverse correlation with grain size. The average grain diameter of samples prepared at 570°C decreased from 51.3μm at ambient temperature to 27.6μm (see fig 8). The great difference in temperature increases the driving force for diffusive phase transformation and decrease the distance that the atoms need to move in order to complete the transformation.[15,16]

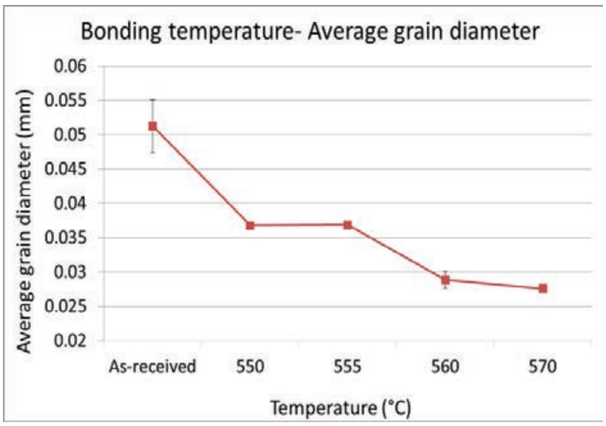

Fig.8. Average grain diameter- bonding temperature relationship.

4. Conclusions

1-A joint was made successfully at 570°C, although brittle IMC ($FeAl_3$) was found at the interface between UNS S32304 and AA-6063. 2-The interaction layer thickness has a proportional relationship with the bonding temperature.3-The oxide layer on the aluminium surface has a negative effect on the dissolution behaviour of Cu wettability with the base metals. Conducting the process in vacuum media could improve the joining process.

Acknowledgements

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